"I Have Come to Praise Charm, not Bury it" [1] [2]

I. I. Bigi

Dept. of Physics, University of Notre Dame du Lac, Notre Dame, IN 46556, U.S.A.
e-mail: ibigi@nd.edu

Abstract

The case for further dedicated studies of charm dynamics is presented as driven by three complementary motivations: core lessons on QCD and nonperturbative dynamics in general can be learnt; those can be applied with great profit in analyses of B decays; charm decays offer a novel portal to New Physics in particular through CP studies.

1 Introduction

There is the feeling in the HEP community that while the study of charm physics had a glorious past – it drove the paradigm shift towards seeing quarks as real dynamical entities rather than objects of mathematical convenience thus providing essential support for the acceptance of the Standard Model (SM) – it has no future with its dull electroweak SM phenomenology: its CKM parameters are known, $D^0 - \bar{D}^0$ oscillations slow at best, CP asymmetries small and loop driven decays extremely rare. Yet I will stress that *dedicated* charm studies are full of promise due to a triple motivation: **(i)** They will provide novel insights into the nonperturbative dynamics of QCD. **(ii)** They will calibrate the theoretical tools for treating B decays. **(iii)** Certain charm transitions open a novel window onto New Dynamics.

The accuracy of the theoretical description is of essential importance in these endeavours. After sketching the theoretical tools and listing lessons to be learnt on QCD in Sect.2, I address searches for New Physics in Sect.3 including a short comment on τ decays before concluding. I can touch on

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[1] With due apologies to the 'Bard'

[2] Invited talk given at FPCP04 in Daegu (Korea), Oct. 5 - 10, 2004

the various issues only briefly. Much more comprehensive discussions and references can be found in Ref.[1].

2   Theory and its Tools

While we do not have a theory *of* charm – i.e. why charm is the way it is – we do have several theoretical tools *for* charm – i.e. for treating charm dynamics. Its mass scale puts it somewhere between the worlds of bona fide heavy and light flavours. The accumulated evidence is that charm is 'somewhat' heavy as naively expected. Quark models are still a useful tool for training our intuition and diagnosing results from lattice QCD (LQCD), but not reliable enough for final answers. Heavy quark expansions (HQE) based on expansions in powers of $1/m_c$ are a priori suspect, since the charm quark mass exceeds the scale of nonperturbative dynamics only moderately. Yet HQE work quite well for *inclusive* transitions like lifetimes – unlike light cone sum rules for *exclusive* semileptonic decays, which fail. This could be due to the fact that the leading nonperturbative contributions to the former start in order $1/m_c^2$ involving local operators only, while the latter contain $\mathcal{O}(1/m_c)$ terms and *non*local correlators.

LQCD is the only existing framework holding out the promise for a truly quantitative treatment of charm *hadrons* that can be improved *systematically* [2]. Furthermore only LQCD can approach the charm scale both from below and above; hopefully charm will emerge as a firm 'bridge' between the treatment of heavy and light flavours. At the same time the unchecked monopoly of a single theoretical technology to deal with nonperturbative dynamics should be viewed by its consumers with serious apprehension despite the siren songs of its producers. Its is therefore essential that the predictions of LQCD be subjected to a whole battery of precise experimental tests, and actually to a whole battery of the. This is happening for charm dynamics due to the comprehensive high quality data being obtained by CLEO-c [3] to be joined by BES III later on and the beauty factories BELLE & BABAR.

2.1   Lessons on QCD

It is no longer adequate to talk about the mass of the charm quark *per se* and identify it with the parameter that appears in a quark *model*. A clean definition that can pass muster by field theory has to be given. The $\overline{MS}$

	$1/m_c$ expect.	theory comments	data
$\frac{\tau(D^+)}{\tau(D^0)}$	$\sim 1 + \left(\frac{f_D}{200\ \text{MeV}}\right)^2 \sim 2.4$	PI dominant	2.54 ± 0.01
$\frac{\tau(D_s^+)}{\tau(D^0)}$	0.9 - 1.3[1.0 - 1.07]	*with* [*without*] WA	1.22 ± 0.02
$\frac{\tau(\Lambda_c^+)}{\tau(D^0)}$	~ 0.5	quark model matrix elements	0.49 ± 0.01
$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)}$	$\sim 1.3 - 1.7$	ditto	2.2 ± 0.1
$\frac{\tau(\Lambda_c^+)}{\tau(\Xi_c^0)}$	$\sim 1.6 - 2.2$	ditto	2.0 ± 0.4
$\frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)}$	~ 2.8	ditto	4.5 ± 0.9
$\frac{\tau(\Xi_c^+)}{\tau(\Omega_c)}$	~ 4	ditto	5.8 ± 0.9
$\frac{\tau(\Xi_c^0)}{\tau(\Omega_c)}$	~ 1.4	ditto	1.42 ± 0.14

Table 1: Lifetime ratios of charm hadrons [1]

mass satisfies this criterion, and one finds

$$\bar{m}_c(m_c) = \begin{cases} 1.19 \pm 0.11\ \text{GeV} & \text{Ref.[5]} \\ 1.14 \pm 0.1\ \text{GeV} & \text{Ref.[6]} \end{cases} ; \tag{1}$$

the first value is based on charmonium sum rules and the second one on moments of semileptonic B decays. The fact that the numbers coming from systematically different observables agree so well supports the a priori conjecture that charm quarks can be treated as 'somewhat heavy', since the scale of nonperturbative dynamics can be characterized by $\mu_{had} \sim 700\text{MeV} \sim N_C \Lambda_{QCD}$. Another indirect one is that about two thirds of $\Gamma(B \to l\nu X_c)$ is given by the two final states D & D^*, which are the ground states in the classification of Heavy Quark Symmetry.

2.1.1 Inclusive Rates

The measured lifetimes of the seven $C = 1$ charm hadrons provide a more quantitative measure for the heaviness of charm. While a priori the HQE might be expected to fail even on the semiquantitative level since $\mu_{had}/m_c \sim 1/2$ (see Eq.(1)), it works surprisingly well in describing the lifetime ratios even for baryons (see Table 1), except for $\tau(\Xi_c^+)$ being about 50 % longer than predicted. This agreement should be viewed as quite nontrivial, since these lifetimes span more than an order of magnitude between the shortest and longest: $\tau(D^+)/\tau(\Omega_c) \simeq 14$.

The SELEX collab. has reported candidates for weakly decaying double charm baryons [4]. It is my judgment that those candidates cannot be $C = 2$ baryons since their reported lifetimes are too short and do not show the expected hierarchy [1].

B_c mesons live in the worlds of beauty as well as of charm. While it had been suggested that binding energy effects lead to a 'long' lifetime above 1 *psec*, the HQE predicts a 'short' one: $\tau(B_c) \sim 0.3 - 0.7$ *psec* with – unlike in life – charm fading faster than beauty [7]. This prediction was supported by a first measurement by CDF and has been confirmed by D0 [8]:

$$\tau(B_c) = 0.45^{+0.12}_{-0.10} \pm 0.12 \; psec \tag{2}$$

Another nontrivial HQE prediction is that the full semileptonic widths of charm *baryons* are *far from universal* – unlike for charm *mesons*. The semileptonic branching ratios of baryons thus do not reflect their lifetimes. It would be highly desirable to measure $\mathrm{BR}_{SL}(\Lambda_c)$ and $\mathrm{BR}_{SL}(\Xi_c^{0,+})$.

While $\Gamma_{SL}(D)$ is ill-suited to determine $|V(cs)|$ precisely, it is an interesting challenge to infer $|V(cd)/V(cs)|$ from the shape of inclusive lepton spectra in $D^0/D^+/D_s^+ \to l\nu X_{s,d}$.

2.1.2   Exclusive Channels

The widths for $D^+/D_s^+ \to l^+\nu$ with $l = \mu, \; \tau$ are controlled by the decay constants f_D and f_{D_s} leading to the following predictions:

$$\mathrm{BR}(D^+ \to \tau^+\nu) \;\; \simeq \;\; 1.1 \cdot 10^{-3} \left(\frac{f_D}{220 \text{ MeV}}\right)^2 \tag{3}$$

$$\mathrm{BR}(D^+ \to \mu^+\nu) \;\; \simeq \;\; 4.3 \cdot 10^{-4} \left(\frac{f_D}{220 \text{ MeV}}\right)^2 \tag{4}$$

$$\mathrm{BR}(D_s^+ \to \tau^+\nu) \;\; \simeq \;\; 5.1 \cdot 10^{-2} \left(\frac{f_{D_s}}{250 \text{ MeV}}\right)^2 \tag{5}$$

$$\mathrm{BR}(D_s^+ \to \mu^+\nu) \;\; \simeq \;\; 5.2 \cdot 10^{-3} \left(\frac{f_{D_s}}{250 \text{ MeV}}\right)^2 \tag{6}$$

The CLEO-c collab. expects to measure these rates and thus f_{D,D_s} with an uncertainty not exceeding a very few percent and compare it with future LQCD predictions of commensurate quality. Both of these goals look quite

attainable and would open the era of *precision* tests of our understanding of nonperturbative dynamics.

As far as other *exclusive* decays are concerned, theoretical tools exist only for semileptonic [nonleptonic] modes with one [two] hadron[s]/resonance[s] in the final states. Since the amplitudes for $D \to l\nu K[\pi]$ etc. depend on $|V(cs)[V(cd)]f_+^{K[\pi]}(q^2)$, there is a dual motivation for a careful analysis: accepting the values of $V(cs)$ and $V(cd)$ inferred from other processes or from three-family unitarity one extracts the formfactor, which can then be compared in its normalization as well as q^2 dependence with LQCD results; or one can employ the latter's prediction to infer the size of $V(cs)$ and $V(cd)$. For that purpose the level of accuracy has to be high to make it competitive. The theoretical prediction for the formfactor can of course be cross checked through its q^2 dependence. Yet that require very precise data since the range in q^2 is quite limited. It will be essential to do such an analysis for D^0, D^+ and D_s^+ Cabibbo allowed as well as suppressed modes and find consistent values for $V(cs)$ and $V(cd)$ before they can be accepted. The CLEO-c program is well equipped to perform such studies [3]. Measuring $D^+/D_s^+ \to l\nu\eta/\eta'$ can give us novel information of the wavefunctions of η and η'; one can also search for glueball candidates G in $D^+/D_s^+ \to l\nu G$.

The treatment of two-body nonleptonic decays poses a formidable theoretical challenge. It would make hardly any sense to rely on *pQCD*; the framework of *QCD factorization* should be tried, although it might fail due to its $\mathcal{O}(1/m_c)$ contributions, which are beyond theoretical control. The pioneering Blok-Shifman analysis [9] based on QCD sum rules should be updated and refined by including $SU(3)_{Fl}$ breaking. A meaningful LQCD analysis has to be fully unquenched. In conclusion: the only tools available at present are quark models; yet their findings have to be taken with quite a rock of salt. For a description of nonleptonic charm decays to claim reliability, it has to succeed on the Cabibbo allowed as well as singly or doubly Cabibbo suppressed levels, including resonant final states with more than one neutral hadron.

Establishing theoretical control over QCD's dynamics will teach us important lessons about nonperturbative dynamics in general, as is relevant for New Physics models based on technicolour to cite but one example.

2.2 'Tooling up' for B Studies

The nonperturbative dynamics driving the exclusive transitions $B \to l\nu D/D^*$ is characterized by the scale m_c, not m_b. Studying charm decays can thus provide important, at times even essential lessons on B decays. A few examples of this connection have to suffice.

Once LQCD's predictions for f_{D,D_s} have (hopefully) been validated on the very few percent accuracy level, one can scale them up with confidence for f_{B,B_s} with great phenomenological benefit for our theoretical interpretation of $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ oscillations.

An analogous strategy will be pursued for exclusive semileptonic B decays. Once LQCD's results on the form factors for $D/D_s \to l\nu M$, $M = K^*, K, \rho, \pi, \eta, ...$ have been validated in their normalization as well as their q^2 dependence, one can extend these methods with enhanced confidence to the treatment of $B \to l\nu\pi/\rho$ etc. to extract $|V(ub)|$.

2.2.1 The '3/2 < 1/2' Puzzle

While the lessons sketched above are common knowledge, this one is not. Semileptonic B decays present us with three motivations to gain a better understanding of charm spectroscopy, the first two experimental and the third one experimental as well as theoretical: (i) Extracting $\Gamma(B \to l\nu X_c)$ and its errors from the data with high accuracy requires good understanding of possible final states to determine detector efficiencies etc.; (ii) likewise for $B \to l\nu D/D^*$ and the feed down from higher charm resonances. (iii) There are classes of sum rules derived from QCD proper that relate the heavy quark parameters appearing in the OPE for inclusive $B \to l\nu X_c$ – like μ_π^2, μ_G^2 etc. – with restricted sums over exclusive channels. They provide rigorous definitions, inequalities and experimental constraints [10]; e.g.:

$$\frac{1}{2} = 2\sum_m |\tau_{3/2}(m)|^2 - 2\sum_n |\tau_{1/2}(n)|^2 \tag{7}$$

$$\mu_G^2(\mu) = 2\sum_m \epsilon_m^2 |\tau_{3/2}(m)|^2 - 2\sum_n \epsilon_n^2 |\tau_{1/2}(n)|^2 , \tag{8}$$

where $\tau_{1/2}$, $\tau_{3/2}$ are the amplitudes for $B \to l\nu D(s_q)$ with $D(s_q)$ a hadronic system beyond the D and D^*, $s_q = 1/2 \& 3/2$ the angular momentum carried by the light degrees of freedom in $D(s_q)$ and ϵ_m the excitation energy of the mth such system above the D with $\epsilon_m \leq \mu$. Eq.(8) manifestly shows that the

$s_q = 3/2$ contributions have to dominate over the $s_q = 1/2$ ones. There were indications in early data – mainly from nonleptonic decays treated under the assumption of factorization – that this hierarchy is not obeyed by the lowest P wave states of which there are four: two narrow $3/2$ (D_1, D_2^*) and two broad $1/2$ states (D_0^*, D_1') [11]. It would be conceivable mathematically that higher resonances would rectify the situation, yet that seems a very contrived solution. Recent BELLE data [12] seem to be consistent with the sum rules. It is important to obtain conclusive data on this issue in semileptonic B decays [8].

Understanding this spectroscopy is important not only in its own right and because heavy quark theory makes nontrivial predictions on it. As stated above it is needed to have full control over the measurements of $B \to l\nu X_c$ (and its moments) as well as $B \to l\nu D^*$. This is desirable also for an exotic scenario: finding the values for $|V(cb)|$ as extracted from $B \to l\nu X_c$ and $B \to l\nu D^*$ to disagree – or the measured moments of the former *not* be described by the same set of heavy quark parameters –, might not point to a true failure of the theoretical description. Instead it might signal the presence of *right*-handed charged current couplings for the b quark!

3 Searching for New Physics

It has often been said that with the 'dull' SM weak phenomenology for charm – slow $D^0 - \bar{D}^0$ oscillations, small CP asymmetries – charm studies allow almost 'zero-background' searches for New Physics. Yet this statement has to be updated carefully since experiments over the last ten years have bounded the oscillation parameters x_D, y_D to fall below very few % and direct CP asymmetries below several %. One should take note that charm is the only *up*-type quark allowing the full range of probes for New Physics, including flavour changing neutral currents: while top quarks do not hadronize [13], in the u quark sector you cannot have $\pi^0 - \pi^0$ oscillations and many CP asymmetries are already ruled out by CPT invariance. My basic contention is the following: *Charm transitions are a unique portal for obtaining a novel access to flavour dynamics with the experimental situation being a priori favourable (except for the lack of Cabibbo suppression)!*

3.1 $D^0 - \bar{D}^0$ Oscillations

$D^0 - \bar{D}^0$ oscillations represent a subtle quantum mechanical phenomenon of great practical importance: it can have a significant impact on extracting the CKM phase ϕ_1/γ from $B^\pm \rightarrow D^{neut}K^\pm$; it provides a probe for New Physics, albeit an ambiguous one; it represents an important ingredient for CP asymmetries arising in D^0 decays due to New Physics.

These phenomena can be characterized by two quantities, namely $x_D = \frac{\Delta M_D}{\Gamma_D}$ and $y_D = \frac{\Delta \Gamma_D}{2\Gamma_D}$. Oscillations are slowed down in the SM due to GIM suppression and $SU(3)_{fl}$ symmetry. Comparing a *conservative* SM bound with the present data

$$x_D(SM), y_D(SM) < \mathcal{O}(0.01) \;\; vs. \;\; x_D|_{exp} < 0.03 \;, \;\; y_D|_{exp} = 0.01 \pm 0.005 \tag{9}$$

we conclude that the search has just now begun. There exists a considerable literature – yet typically with several ad-hoc assumptions concerning the nonperturbative dynamics. It is widely understood that the usual quark box diagram is utterly irrelevant due to its untypically severe GIM suppression $(m_s/m_c)^4$. A systematic analysis based on an OPE has been given in Ref.[14] in terms of powers of $1/m_c$ and m_s. Contributions from higher-dimensional operators with a much softer GIM reduction of $(m_s/\mu_{had})^2$ (even m_s/μ_{had} terms could arise) due to 'condensate' terms in the OPE yield

$$x_D(SM)|_{OPE} \,, \;\; y_D(SM)|_{OPE} \sim \mathcal{O}(10^{-3}) \;. \tag{10}$$

Ref.[15] finds very similar numbers, albeit in a quite different approach.

While one predicts similar numbers for $x_D(SM)$ and $y_D(SM)$, one should keep in mind that they arise in very different dynamical environments. ΔM_D is generated from off-shell intermediate states and thus is sensitive to New Physics, which could produce $x_D \sim \mathcal{O}(10^{-2})$. $\Delta \Gamma_D$ on the other hand is shaped by on-shell intermediate states; while it is hardly sensitive to New Physics, it involves much less averaging or 'smearing' than ΔM_D making it thus much more vulnerable to violations of quark-hadron duality. Observing $y_D \sim 10^{-3}$ together with $x_D \sim 0.01$ would provide intriguing, though not conclusive evidence for New Physics, while $y_D \sim 0.01 \sim x_D$ would pose a true conundrum for its interpretation. Yet even those have to be measured for a proper analysis of $B^\pm \rightarrow D^{neut}K^\pm$, preferably down to the 10^{-3} level.

3.2 CP Violation

Since the baryon number of the Universe implies the existence of New Physics in CP violating dynamics, it would be unwise not to undertake dedicated searches for CP asymmetries in charm decays, where the 'background' from known physics is small: within the SM the effective weak phase is highly diluted, namely $\sim \mathcal{O}(\lambda^4)$, and it can arise only in singly Cabibbo suppressed transitions, where one expects them to reach the 0.1 % level; significantly larger values would signal New Physics. *Any* asymmetry in Cabibbo allowed or doubly suppressed channels requires the intervention of New Physics – except for $D^{\pm} \to K_S \pi^{\pm}$ [1], where the CP impurity in K_S induces an asymmetry of $3.3 \cdot 10^{-3}$. Several facts actually favour such searches: strong phase shifts required for direct CP violation to emerge in partial widths are in general large as are the branching ratios into relevant modes; finally CP asymmetries can be linear in New Physics amplitudes thus enhancing sensitivity to the latter. As said above, the benchmark scale for KM asymmetries in singly Cabibbo suppressed partial widths is 0.1%. This does not exclude the possibility that CKM dynamics might exceptionally generate an asymmetry as 'large' as 1% in some special cases. It is therefore essential to analyze a host of channels.

Decays to final states of *more than* two pseudoscalar or one pseudoscalar and one vector meson contain more dynamical information than given by their widths; their distributions as described by Dalitz plots or *T-odd* moments can exhibit CP asymmetries that can be considerably larger than those for the width. Final state interactions while not necessary for the emergence of such effects, can fake a signal; yet that can be disentangled by comparing *T-odd* moments for CP conjugate modes. I view this as a very promising avenue, where we still have to develop the most effective analysis tools for small asymmetries.

CP violation involving $D^0 - \bar{D}^0$ oscillations can be searched for in final states common to D^0 and $\bar{D}^0$ decays like CP eigenstates – $D^0 \to K_S \phi$, $K^+ K^-$, $\pi^+ \pi^-$ – or doubly Cabibbo suppressed modes – $D^0 \to K^+ \pi^-$. The CP asymmetry is controlled by $\sin \Delta m_D t \cdot \text{Im}(q/p) \bar{\rho}(D \to f)$; within the SM both factors are small, namely $\sim \mathcal{O}(10^{-3})$, making such an asymmetry unobservably tiny – unless there is New Physics! One should note that this observable is linear in x_D rather than quadratic as for CP insensitive quantities. $D^0 - \bar{D}^0$ oscillations, CP violation and New Physics might thus be discovered simultaneously in a transition.

One wants to reach the level at which SM effects are likely to emerge, namely down to time-*dependent* CP asymmetries in $D^0 \to K_S\phi$, K^+K^-, $\pi^+\pi^-$ $[K^+\pi^-]$ down to 10^{-5} $[10^{-4}]$ and *direct* CP asymmetries in partial widths and Dalitz plots down to 10^{-3}.

3.3   Short Comment on τ Decays

Like charm hadrons the τ lepton is often viewed as a system with a great past, but hardly a future. Again I think this is a very misguided view and I will illustrate it with two examples.

If baryogenesis is a secondary phenomenon driven by primary leptogenesis, one needs CP violation in the lepton sector. In my judgment τ decays – together with electric dipole moments for leptons and possibly ν oscillations – provide the best stage to search for other manifestations of these dynamics directly.

Searching for $\tau^\pm \to \mu^\pm\mu^+\mu^-$ (and its variants) – processes forbidden in the SM – is particularly intriguing, since it involves only 'down-type' leptons of the second and third family and is thus the complete analogy of the quark lepton process $b \to s\bar{s}s$ driving $B_s \to \phi K_S$, which has recently attracted such strong attention. Following this analogy literally one guestimates BR($\tau \to 3\mu$) $\sim 10^{-8}$ to be compared with the present bound from BELLE [16]

$$\mathrm{BR}(\tau \to 3\mu) \leq 2 \cdot 10^{-7} \ . \tag{11}$$

It would be very interesting to know what the τ production rate at the hadronic colliders is and whether they could be competitive or even superior with the B factories in such a search.

4   Conclusions and Outlook

The SM has scored qualitatively new successes in flavour dynamics since the beginning of this millenium [17]. Yet we have to admit that we 'know so much, yet understand so little'; i.e., the SM provides an incomplete picture of Nature's 'Grand Design'. I firmly believe that we need further hints from Nature to get a more complete picture. Dedicated and comprehensive studies of the decays of charm mesons and τ leptons will prove essential in our endeavour. They will sharpen our understanding of QCD and nonperturbative dynamics in general and validate our tools for treating B decays with

the required accuracy. Last, not least they offer the persistent student the promise to identify the intervention of New Physics, in particular in the area of CP violation. The observed baryon number of the universe and the 'strong CP problem' provide intriguing evidence for the presence of New Physics.

Acknowledgments

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